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Heavy Flavour Physics: On Its More Than 50 Years Of History, Its Future And The Rio Manifesto [1]

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Abstract

After a reminder about how $\Delta S \neq 0$ physics has been instrumental for the development of the Standard Model I sketch theoretical technologies for dealing with nonperturbative QCD in heavy flavour decays and state predictions for CP odd effects as they were made in 1998. I review the exciting developments in heavy flavour physics as presented at this conference. A central message is presented in the 'Rio Manifesto' where I recapitulate the lessons we have learnt from charm physics, point out the special role future dedicated charm studies can play in revealing the presence of New Physics and give an introduction to the relevant phenomenology focussed on CP studies.

Contents

[1] Summary Talk given at HQ2K 'Heavy Quarks at Fixed Target 2000', Rio de Janeiro, Brazil, Oct. 9 -12, 2000

1 Introduction

In the dawn of history, in a time long ago and a place far away, in October 1946 Butler and Rochester saw a V^0 in their cloud chamber that had been exposed to cosmic rays [1]:

$$K^0 \to \pi^+\pi^- \tag{1}$$

This was the beginning of 'heavy quarks at fixed target', and things have never been the same again. The comprehensive study of the dynamics of strangeness has revealed the following fundamental features:

- The $\tau - \theta$ puzzle led to the realization that parity is not conserved in nature.
- The observation that the production rate exceeds the decay rate by many orders of magnitude – this was the origin of the name 'strange particles' – was explained through postulating a new quantum number – 'strangeness' – conserved by the strong, though not the weak forces. This was the beginning of the second quark family.
- The absence of flavour-changing neutral currents was incorporated through the introduction of the quantum number 'charm', which completed the second quark family.
- CP violation finally led to postulating yet another, the third family.

All of these elements which now form essential pillars of the Standard Model (SM) were New Physics at *that* time! While strange quarks were thus instrumental for formulating the Standard Model, charm quarks provided important consistency checks; finally with the discovery of beauty quarks (and τ leptons) the CKM ansatz became the standard paradigm for CP violation with the only unknown about the top quark being its mass.

The present status can be characterized as follows: All six quark as well as lepton flavours have unambiguously been discovered now. A quite full SM profile is known about charm, the first predicted flavour,and it happens to be a bit on the dull side – a point I will return to later. About beauty quarks a lot is known, but its SM profile is not complete, mainly because the latter is so exciting; major efforts are under way to fill it out. Little is directly known about top quarks beyond their existence, their mass and their affinity for beauty quarks; this will improve.

The SM forms a renormalizable and in that sense self-consistent theory. It also works amazingly well. Heavy quark and lepton flavours constitute essential elements of it – and central mysteries:

- Why is there a family structure relating quarks and leptons?
- Why is there more than one family, why three, is three a fundamental parameter?
- What is the origin of the observed pattern in the quark (and lepton) masses and the CKM parameters? This pattern can hardly have come about by accident.
- Why are neutrinos massless – or aren't they?

It certainly would represent an amazing triumph of the human mind if pure thinking would lead us to the explanations underlying these mysteries; however I am skeptical about such an outcome. It seems much more likely that we need to elicit more answers from nature through further experimentation, however delphic nature's answers might turn out. Dedicated studies of heavy flavour dynamics represent high sensitivity searches for indirect manifestations of New Physics.

The good news are that we are at a decisive period of flavour physics:

- *Direct* CP violation has been established in K_L decays.
- We are on the brink of observing the large CP asymmetries predicted by the SM for certain B decays.
- Studies of charm decays have finally reached a sensitivity level where manifestations of New Physics could very realistically show up.
- There is a good chance that at last leptons are about to reveal a nontrivial flavour structure.

My talk will be organized as follows: after sketching the status of theoretical technologies for heavy flavour physics in Sect. 2, I summarize the new results we have heard about the dynamics of strange and beauty hadrons in Sects. 3 and 4, respectively; in Sect. 5 I present the 'Rio Manifesto' as a very central part of my talk, where I recapitulate the glorious past of charm quarks and explain the reasons behind my optimism that the best days of charm are still to come.

2 Theoretical tools

2.1 QCD technologies of the 1990's

Since we have to study the decays of quarks bound inside hadrons, we have to deal with nonperturbative dynamics [2] – a problem that in general has not been brought under theoretical control. Yet we can employ various theoretical technologies based rather squarely on QCD that allow to treat nonperturbative effects in special situations:

- For *strange* hadrons where $m_s \leq \Lambda_{QCD}$ one invokes chiral perturbation theory.
- For *beauty* hadrons with $m_b \gg \Lambda_{QCD}$ one can employ $1/m_b$ expansions in various incarnations; they should provide us with rather reliable results, whenever an operator product expansion can be applied [3].
- It is natural to extrapolate such expansions down to the charm scale. This has to be done with considerable caution, though: while the charm quark mass exceeds ordinary hadronic mass scales, it does not do so by a large amount.
- Lattice QCD on the other hand is most readily set up at ordinary hadronic scales; from those one extrapolates *down* towards the chiral limit (which represents a nontrivial challenge) and *up* to the charm scale and beyond.
- I want to direct your attention to the special position of charm. While $1/m_c$ expansions extending from above are a priori of somewhat dubious numerical reliability, unquenched lattice calculations – with some effort – can reach the charm scale from below. For the later discussion I want to note charm can thus take on a central role as a bridge between different theoretical technologies.

I do not consider quark models state-of-the-art anymore in general. Yet as long as one remains aware of their limitations and exercises good judgement, they can serve many important purposes, one being to educate our intuition. Yet for that to happen one has to go beyond a naive formulation, as nicely demonstrated in Törnkquist's talk [4].

[2]Since top quarks decay before they can hadronize, their interactions can be treated perturbatively [2].

Let me add a few more specific comments:

Lattice QCD, which originally had been introduced to prove confinement and bring hadronic spectroscopy under computational control is now making major contributions to heavy flavour physics. This can be illustrated with very recent results on decay constants where the first *un*quenched results (with two dynamical quark flavours) have become available [5]:

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$$f(D_s) = \begin{cases} 240 \pm 4 \pm 24 \text{ MeV lattice QCD} \\ 275 \pm 20 \text{ MeV lattice QCD} \\ 269 \pm 22 \text{ MeV, world average of data on } D_s \to \mu\nu \end{cases} \tag{2}$$

-
$$f(B) = 190 \pm 6 \pm 20^{+9}_{-0} \text{ MeV, lattice QCD} \tag{3}$$
$$f(B_s) = 218 \pm 5 \pm 26^{+9}_{-0} \text{ MeV, lattice QCD} \tag{4}$$

The $1/m_Q$ expansions have become more refined and reliable qualitatively as well as quantitatively:

- The b quark mass has been extracted from data by three different groups following a pioneering study of Voloshin [12]; their findings, when expressed in terms of the socalled 'kinetic' mass, read as follows:

$$m_b^{\rm kin}(1\,\text{GeV}) = \begin{cases} 4.56 \pm 0.06 \text{ GeV [6],} \\ 4.57 \pm 0.04 \text{ GeV [7],} \\ 4.59 \pm 0.06 \text{ GeV [8]} \end{cases} \tag{5}$$

  The error estimates of 1 - 1.5 % might be overly optimistic (as it often happens), but not foolish. Since all three analyses use basically the same input from the $\Upsilon(4S)$ region, they could suffer from a common systematic uncertainty, though.

- For the formfactor describing $B \to l\nu D^*$ at zero recoil one has the following results:

$$F_{D^*}(0) = \begin{cases} 0.89 \pm 0.08 \text{ [9],} \\ 0.913 \pm 0.042 \text{ [10],} \\ 0.935 \pm 0.03 \text{ [11],} \end{cases} \tag{6}$$

  where the last number has been obtained in lattice QCD.

There is a natural feedback between lattice QCD and $1/m_Q$ expansions: by now both represent mature technologies that are defined in Euclidean rather than Minkowskian space; they share some expansion parameters, while differing in others; lattice QCD can evaluate hadronic matrix elements that serve as input parameters to $1/m_Q$ expansions.

It has been accepted for a long time that heavy flavour decays can serve as high *sensitivity* probes for New Physics. I feel increasingly optimistic that our tools will be such that that they will provide us even with high *accuracy* probes!

In describing nonleptonic two-body modes $B \to M_1 M_2$ valuable guidance has been provided over the years by symmetry considerations based on $SU(2)$ and to a lesser degree $SU(3)$. Phenomenological models have played an important role [13, 14]; more often than not they involve factorization as a central assumption. As already said, such models still play an important role in widening our horizon when used with common sense. Yet the bar has been raised for them by the emergence of a new theoretical framework for dealing with these decays. The essential precondition for this framwork is the large energy release, and it invokes concepts like 'colour transparency'. While those have been around for a while, only now they are put into a comprehensive framework. Two groups have presented results on this [15, 16]. The common feature in their approaches is that the decay amplitude is described by a kernel containing the 'hard' interaction given by a perturbatively evaluated effective Hamiltonion folded with form factors, decay constants and ligh-cone distributions into which the long distance effects are lumped; this *factorization* is symbolically denoted by

$$\langle M_1 M_2 | H | B \rangle = f_{B \to M_1} f_{M_2} T^H * \Phi_{M_2} + ... \tag{7}$$

The two groups differ in their dealings with the soft part: KLS invoke Sudakov form factors to shield them against IR singularities. In the BBNS approach on the other hand *no* IR singularities occur to leading order in $1/m_b$. They do arise in nonleading orders where they could be dealt with by introducing low energy parameters. It is not surprising that the two groups arrive at different conclusions: while BBNS infer final state interactions to be mostly small in $B \to \pi\pi, K\pi$ with weak annihilation being suppressed, KLS argue for weak annihilation to be important with final state interactions *not* always small.

The trend of these results have certainly the ring of truth for me: e.g., while factorization represents the leading effect in most cases (including $B \to D\pi$), it is not of universal quality. One should also note that the *non*-factorizable contributions move the predictions for branching ratios towards the data – a feature one could not count on *a priori*. It is not clear to me yet whether the two approaches are complementary or irreconcilable. Secondly one should view these predictions as preliminary: a clear disagreement with future data should be taken as an opportunity for learning rather than for discarding the whole approach. This is connected with a third point: there are corrections of order μ/m_b which are beyond our computational powers. Since μ might be as large as 0.5 - 1 GeV, they could be sizeable.

In summary: the theoretical technologies exist to describe two classes of decays, namely fully inclusive transitions on one hand – lifetimes, semileptonic widths, lepton spectra in inclusive semileptonic decays – and the simplest exclusive modes – semileptonic modes with a single hadron or resonance in the final state and two-body nonleptonic modes. Yet for all other modes – nonresonant three-body channels etc.

– all we have are models of quite uncertain footing; it probably will take another breakthrough to bring them under theoretical control.

2.2 On Quark-hadron duality

Most calculations are based on the concept of quark-hadron duality (QHDu) in one form or another: when calculating a rate on the quark-gluon level QHDu is invoked to equate the result with what one should get for the corresponding process expressed in hadronic quantities.

This concept is very successful for processes initiated by hard dynamics: $e^+e^- \to$ *hadrons* well above thresholds, the widths for $Z^0 \to b\bar{b}$ or $c\bar{c}$ jets or $W \to c\bar{s}$ jets etc. For the purpose of treating beauty and charm decays two new more specific questions arise in applying $1/m_Q$ expansions: (i) How low can the scale be for QHDu to still apply? (ii) QHDu *cannot* be exact. The question is how large are actually the uncertainties that enter here [17, 18].

The $1/m_Q$ expansion should certainly work well for beauty, yet for charm the situation is much more iffy, and realistically one can hope for no more than semi-quantitative results there. QHDu represents an approximation the quality of which is process-dependant and increases with the amount of averaging or 'smearing' over hadronic channels.

There is a lot of folklore concerning QHDu, but no general theory. That is not surprising: for QHDu can be addressed in a quantitative fashion only *after* nonperturbative effects have been brought under control, and that has happened only recently in beauty decays. Considerable insight exists into the physical origins of QHDu violations: (i) They are caused by the exact location of hadronic thresholds that are notoriously hard to evaluate. Such effects are implemented through 'oscillating terms'; i.e., the fact that innocuous, since suppressed contributions $\exp(-m_Q/\Lambda)$ in Euclidean space turn into dangerous while unsuppressed $\sin(m_Q/\Lambda)$ terms in Minkowski space. (ii) There is bound to be some sensitivity to 'distant cuts' [19]. (iii) The validity of the $1/m_c$ expansion arising in the description of $B \to l\nu D^*$ is far from guaranteed.

Based on general considerations and analyses in model field theories like the 't Hooft model (QCD in 1+1 dimensions with $N_C \to \infty$) one can say the following: while one would not be overly surprised if *nonleptonic* decays even of beauty hadrons were to exhibit significant violations of QHDu, one has good reason to be confident that *inclusive semileptonic* decays of beauty hadrons are described by $1/m_Q$ expansions quite accurately. This is further re-inforced by the successful treatment of inclusive τ decays where an accurate value for the strong coupling α_S has been extracted in full agreement with determinations at high energies like at Z^0.

2.3 CKM matrix – present and future

PDG2000 lists the following values for the CKM matrix elements as 90% C.L. ranges:

$$|V_{CKM}| = \begin{pmatrix} 0.9750 \pm 0.0008 & 0.223 \pm 0.004 & 0.003 \pm 0.002 \\ 0.222 \pm 0.003 & 0.9742 \pm 0.0008 & 0.040 \pm 0.003 \\ 0.009 \pm 0.005 & 0.039 \pm 0.004 & 0.9992 \pm 0.0002 \end{pmatrix} \tag{8}$$

Without imposing three-family unitarity the numbers in particular for the top couplings are much less restrictive:

$$|V_{CKM}| = \begin{pmatrix} 0.9735 \pm 0.0013 & 0.220 \pm 0.004 & 0.003 \pm 0.002 & ... \\ 0.226 \pm 0.007 & 0.880 \pm 0.096 & 0.040 \pm 0.003 & ... \\ 0.05 \pm 0.04 & 0.28 \pm 0.27 & 0.5 \pm 0.49 & ... \\ ... & ... & ... & ... \end{pmatrix} \tag{9}$$

PDG2000 quotes [3]

$$\left| \frac{V(ts)}{V(td)} \right| > 4.17 \tag{10}$$

as inferred from the lower bound on $\Delta m(B_s)$. Very recently somewhat higher values have been stated: $|V(ts)/V(td)| > 4.6$.

An optimist might say that there is intriguing though not conclusive evidence that the first glimpse of B_s oscillations has been caught with $\Delta m(B_s) \sim 17.5$ ps^{-1}. If so, D0 and CDF should have little trouble establishing it soon [20].

Theoretically the cleanest way to extract $|V(td)|$ is measuring the branching ratio for $K^+ \to \pi^+ \nu\bar{\nu}$. Within the SM one predicts [21]

$$0.5 \cdot 10^{-10} \leq \mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \leq 1.2 \cdot 10^{-10} \tag{11}$$

BNL experiment E789 has seen one celebrated event corresponding to $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.5^{+3.4}_{-1.2} \cdot 10^{-10}$. Its final sample will have a single event sensitivity of about $0.7 \cdot 10^{-10}$; its successor, E 949, is expected to yield around 10 events for the SM branching ratio [22]. At Fermilab the experiment CKM has been proposed to measure $K^+ \to \pi^+ \nu\bar{\nu}$ at the 100 event level [23]. These are truly heroic efforts!

I would like to add three comments here:

1. The brandnew CLEO number for $|V(cb)|$ from $B \to l\nu D^*$ – $|V(cb) F_{D^*}(0)| = (42.4 \pm 1.8 \pm 1.9) \times 10^{-3}$ – falls outside the 90% C.L. range stated by PDG2000 for the expected values of $F_{D^*}(0)$.

2. The OPAL collaboration has presented a new *direct* determination of $|V(cs)|$ from $W \to H_c X$: $|V(cs)| = 0.969 \pm 0.058$ [24].

[3] Since there are common uncertainties in $|V(td)|$ and $|V(ts)|$ this ratio is not obtained directly from Eq.(8).

3. Using these values one finds

$$|V(ud)|^2 + |V(us)|^2 + |V(ub)|^2 = 1.000 \pm 0.003 \ , \tag{12}$$

which is perfectly consistent with the unitarity of the CKM matrix. Yet using instead $|V(ud)| = 0.9740 \pm 0.0005$ as extracted from nuclear $0^+ \to 0^+$ transitions, one obtains [25]

$$|V(ud)|^2 + |V(us)|^2 + |V(ub)|^2 = 0.9968 \pm 0.0014 \ , \tag{13}$$

i.e., a bit more than a $2\,\sigma$ deficit in the unitarity condition.

With these input values for the CKM parameters one can make predictions on CP asymmetries, at least in principle and to some degree. I will confine myself to a few more qualitative comments.

- If there is a single CP violating phase δ as is the case in the KM ansatz one can conclude based on the $\Delta I = 1/2$ rule: $\epsilon'/\epsilon \leq 1/20$. The large top mass – $m_t \gg M_W$ – enhances the SM prediction for ϵ considerably more than for ϵ' for a given δ and therefore on quite general grounds

$$\epsilon'/\epsilon \ll 1/20 \ . \tag{14}$$

- Of course the KM predictions made employed much more sophisticated theoretical reasoning. Before 1999 they tended to yield – with few exceptions [26] – values not exceeding 10^{-3} due to sizeable cancellations between different contributions.

- Once the CKM matrix exhibits the *qualitative* pattern given in Eq.(8), it necessarily follows that certain B_d decay channels will exhibit CP asymmetries of order unity. To be more specific one can combine what is known about $V(cb)$, $V(ub)$, $V(ts)$ and $V(td)$ from semileptonic B decays, $B_d - \bar{B}_d$ oscillations and bounds on $B_s - \bar{B}_s$ oscillations with or without using ϵ to construct the CKM unitarity triangle describing B decays. A crucial question to which I will return later centers on the proper treatment of theoretical uncertainties. A typical example is [27]:

$$\sin 2\phi_1[\beta] = 0.716 \pm 0.070 \ , \ \sin 2\phi_2[\alpha] = -0.26 \pm 0.28 \tag{15}$$

3 CP violation in strange and in beauty transitions

3.1 $\Delta S \neq 0$

Direct CP violation has now been established in K_L decays:

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon'}\right) = \begin{cases} (2.80 \pm 0.41) \cdot 10^{-3} & \text{KTeV[28]} \\ (1.40 \pm 0.43) \cdot 10^{-3} & \text{NA48[29]} \end{cases} \tag{16}$$

however its exact size is still uncertain. It is a discovery of the first rank irrespective of what theory does or does not say.

Our theoretical interpretation of the data is very much in limbo. As I had argued before a rather small, but nonzero value is a natural expectation of the KM ansatz. To go beyond such a qualitative statement, one has to evaluate hadronic matrix elements; apparently one had underestimated the complexities in this task. One intriguing aspect in this development is the saga of the $\Delta I = 1/2$ rule: formulated in a compact way [30] it was originally expected to find a simple dynamical explanation; several enhancement factors were indeed found, but the observed enhancement could not be reproduced in a convincing manner; this problem was then bracketed for some future reconsideration and it was argued that ϵ'/ϵ could be predicted while ignoring the $\Delta I = 1/2$ rule. Some heretics – 'early' ones [31] and 'just-in-time' ones [32] – however argued that only approaches that reproduce the observed $\Delta I = 1/2$ enhancement can be trusted to yield a re alistic estimate of ϵ'/ϵ. In particular it had been suggested that the σ – the scalar $\pi\pi$ resonance we have been hearing a lot of at this meeting – plays a significant role here [31].

In all fairness one should point out that due to the large number of contributions with different signs theorists are facing an unusually complex situation. One can hope for lattice QCD to come through, yet it has to go beyond the quenched approximation, which will require more time.

Direct CP violation will emerge also in hyperon decays. One can compare partial widths for CP conjugate channels. Yet their differences are given by the interference between $\Delta I = 1/2$ and $\Delta I = 3/2$ amplitudes and thus suppressed by the $\Delta I = 1/2$ enhancement similar to the situation with ϵ' in $K_L \to \pi\pi$. The HyperCP experiment instead compares the angular distributions of protons and antiprotons in the decay sequences $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ and $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+ \to \bar{p}\pi^+\pi^+$, respectively [33]. An asymmetry there depends on the interference between S- and P-waves; it is therefore not reduced by the $\Delta I = 1/2$ rule and could conceivably exceed the 10^{-4} level. HyperCP aims for a statistical accuracy of $1.4 \cdot 10^{-4}$ in the combined asymmetry parameter $\mathcal{A}_{\Xi\Lambda}$; so far they have achieved:

$$\mathcal{A}_{\Xi\Lambda} = (-1.6 \pm 1.3 \pm 1.6) \cdot 10^{-3} \tag{17}$$

The KAMI experiment proposed for FNAL[34] aims at measuring the branching ratio for $K_L \to \pi^0\nu\bar{\nu}$ which can proceed only due to CP violation. Within the SM with the CKM implementation of CP violation one predicts

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.1 \pm 1.3) \cdot 10^{-11} \tag{18}$$

Such a project has to overcome daunting experimental challenges. On the other hand it presents a highly intriguing theoretical perspective: it would provide an independant route for extracting $\sin 2\phi[\beta]$. Similar plans are being examined at BNL.

KTeV and NA48 will analyze various rare K_L and K_S modes [35, 36]. Some are directly relevant to the CP phenomenology while others build a broader data base for interpreting future measurement. Using the literary figure of the "Cathedral Builders' paradigm" I might add the following comment about the latter class of measurements: while only engineers might perceive their beauty, they are important elements for the foundations and thus for the whole building.

3.2 $\Delta B \neq 0$

The second new element in 1999 was the start-up of the new asymmetric B factories BaBar and BELLE. Their first results leave us in limbo:

$$\sin 2\phi_1[\beta] = 0.45^{+0.43+0.07}_{-0.44-0.09} \text{ BELLE} \tag{19}$$

$$\sin 2\phi_1[\beta] = 0.12 \pm 0.37 \pm 0.09 \text{ BaBar} \tag{20}$$

to be compared with the earlier data [38]

$$\sin 2\phi_1[\beta] = 0.79^{+0.41}_{-0.44} \text{ CDF} \tag{21}$$

No definite conclusions can be drawn yet. However the amazingly speedy start-up of the two asymmetric beauty factories and the new runs of D0 and CDF should should produce quite specific results within the next two years [37, 38].

Nevertheless it is tempting to speculate 'what if no asymmetry is observed in $B \to \psi K_S$; i.e., if one finds, say, $|\sin 2\phi[\beta]| \leq 0.05$. We would know there had to be New Physics present since otherwise we could no longer accommodate $K_L \to \pi\pi$. One would have to raise the basic question why the CKM phase is so suppressed, unless there is an almost complete cancellation between KM and New Physics forces in $B \to \psi K_S$; this would shift then the CP asymmetry in $B \to \pi\pi$, $\pi\rho$.

3.3 Probing for New Physics

As already stated, I expect that by 2002 CP violation will be stablished in at least one B decay mode, presumably in $B_d \to \psi K_S$. This will be a discovery of the very first rank – in all likelihood the first observation of CP violation outside the K_L system – yet that will be far from the end of it!

Experiments at the upgraded B factories at KEK and SLAC together with new experiments at the LHC – LHC-B – and at FNAL – BTeV – are expected to achieve experimental accuracies of a few percent, and they will measure many more observables. At the same time I expect that over the next five years or so we will be able to predict Standard Model effects with a few percent accuracy due to improved

theoretical tools and new measurements of CP *in*sensitive rates. This will provide us with high sensitivity probes for the presence of New Physics.

There are precedents for establishing the presence of New Physics in such an *indirect* way in heavy flavour decays: based on the apparent absence of flavour changing neutral currents some courageous souls [39] postulated the existence of charm quarks; the occurance of $K_L \to \pi\pi$ lead to the conjecture that even a third family of quarks had to exist [40]. However in all those cases we could rely on a *qualitative* discrepancy; i.e., the difference between observed and predicted rate amounted to several orders of magnitude or the predicted rate was zero – as for $K_L \to \pi\pi$.

In the decays of beauty hadrons we predict many large or at least sizeable effects, and realistically in most cases we can expect differences well below an order of magnitude only! Thus we will have to deal with a novel challenge not encountered before; it will require that we gain quantitative control over that most evasive class of entities – theoretical uncertainties. I am confident we will make great progress in that respect. My optimism is not based on hoping that novel theoretical breakthroughs will occur – they might. But what will empower us is the fact that so many different types of observables can be measured in beauty decays. There are actually six KM unitarity triangles [41], and several of their angles can be measured in the dedicated and comprehensive research program that is being undertaken world-wide. Our analysis will then be able to invoke overconstraints – the most effective weapon in our arsenal against systematic uncertainties in general.

4 The Rio Manifesto – "I have come to praise c(harm), not to bury it"

A manifesto usually consists of three parts, namely (i) an analysis of past history, (ii) lessons derived for the present and (iii) a plan of action for the future. Furthermore it is usually expressed with great conviction or at least great passion. In my evaluation of charm physics I will largely, but not completely follow this pattern: I will describe the past contributios of charm physics and point out its potential for leading to fundamentally new insights in the future. However, I will refrain from even attempting to sketch a concrete plan for future action. Yet I have to admit that I feel a certain passion about these issues. I have made this part as self-contained as possible.

4.1 Charm in the present Pantheon of fundamental physics [42]

The existence of charm quarks had been postulated in 1964 (the year CP violation was discovered) mainly to complete the quark lepton correspondance, namely to match the four lepton flavours – electrons, muons and their respective neutrinos –

with four quark flavours [43]. In 1970 a more specific motivation was added, namely to suppress flavour changing neutral currents [39]. I should add, though, that these arguments were not embraced by everybody; a not untypical attitude at that time is expressed in the quote: "Nature is smarter than Shelley and can do without charm".

In 1971 charm hadrons were first seen in cosmic ray data by Niu and his group at Nagoya University [44], then in 1974 by the HPW collaboration through dimuons in deep inelastic neutrino scattering; hidden charm emerged in the $J\psi$ resonance that gave rise to the 'October revolution' of 1974, before open charm was identified at SPEAR in 1976.

After that things were never the same again:

- It became the standard paradigm to describe subnuclear events in terms of quark-gluon degrees of freedom where the latter were now seen as quite physical objects rather than merely mathematical entities.
- Postulating new quark flavours turned into a popular sport, at least for some time.
- Theorists grew more confident in tackling the description of nonleptonic weak decays, at least for charm hadrons.

One very early fruit of this change in attitude was the KM paper [40] on CP violation. It postulated, as one of its scenarios for implementing CP violation, at least three families when only 1.5 families had been widely accepted in the community. This jump was helped considerably by two convictions held at Nagoya University at that time, but not at many other places: due to Sakata and his school, the notion of quarks as real rather than merely mathematical had been readily accepted, as had been the existence of charm due to the discovery of Niu [44].

Soon it was conjectured that due to the charm quark mass exceeding ordinary hadronic scales, strong interaction effects should become more tractable in total lifetimes as well as nonleptonic two-body decay modes and in lepton spectra of semileptonic decays of charm hadrons.

With charm being the second member of a quark family its Standard Model weak phenomenology becomes quite predictable and a bit on the dull side as explained in more detail later. It is typically viewed as the 'St. John the Baptist' of heavy flavour physics, i.e., the precursor of greater things to come. It indeed filled this role admirably. There were three *experimental* achievements in that vein:

- Microvertex technology was developed to resolve secondary decay vertices corresponding to lifetimes of order 10^{-13} sec. This technology has turned into a central tool for studying beauty decays with lifetimes of order 10^{-12} sec (and lower γ values).
- Various flavour tagging techniques have been developed, namely both 'same-side' flavour tagging – $D^* \to D\pi$ – as well as 'opposite-side' flavour tagging –

$\bar{H}_c D \to (l^-/K^+X)_{\bar{H}_c} D$; the corresponding techniques have become essential in studying $B - \bar{B}$ oscillations and CP violation.

- The concept of turning e^+e^- 'sweatshops' into 'factories' has been pioneered for charm with $e^+e^- \to J/\psi$ and $e^+e^- \to \psi'' \to D\bar{D}$ pointing the way to $e^+e^- \to \Upsilon(1S - 3S)$ and $e^+e^- \to \Upsilon(4S) \to B\bar{B}$.

New insights were gained also on the *theory* side:

- Basic phenomenological concepts like the so-called 'Pauli Interference' (PI) [45] or 'Weak Annihilation' (WA) [46] were developed for treating weak lifetimes of charm *hadrons*.
- Likewise for exclusive nonleptonic two-body channels: the concepts of factorization, class I, II and III transitions [13].
- Certain aspects of heavy quark symmetry were glimpsed first in the charm system.
- The role of $SU(3)_{Fl}$ symmetry and its limitations in exclusive versus inclusive transitions were studied.
- The AC^2M^2 model for semileptonic decay *spectra* was first put forward [47].
- It was realized that charm physics provides a wide and novel area for lattice QCD.

These considerations later were applied to the dynamics of beauty hadrons with $1/m_Q$ expansions providing justification.

4.2 Present profile of charm dynamics

There is a triple motivation for heavy flavour studies in general, and it applies to charm in particular:

- It provides a novel probe of the *strong* interactions in charm production, hadronic spectroscopy and the weak decays of charm hadrons.
- One determines fundamental parameters, namely CKM parameters and the charm quark mass.
- One searches for manifestations of New Physics in rare decays, oscillations and CP asymmetries.

4.2.1 QCD aspects

(i) Charm production

A large body of high quality data has been accumulated on photo- and hadroproduction of charm as reviewed by Appel [48]. Distributions over a wide kinematical range have been studied, including production asymmetries. The increase in statistics has lead to a new level of sophistication:

- Charm-anticharm correlations are analyzed in large samples where both charm hadrons have been reconstructed.
- The polarizations of charm baryons and of charmonia are measured.

Alas, no *comprehensive* theoretical analysis has been performed. I am not suggesting that a true treasure is hidden there that will bring instant fame to the theorist who uncovers it; however I do believe that this field can be mined for valuable information.

Charm acts as a probe in two ways here: its mass provides a (relatively) hard scale for the dynamics and thus a new handle on the strong interactions and the hadronization driven by them. At the same time charm production depends on the structure of the beam and the target, namely their gluon and $q\bar{q}$ sea distributions. Charm production thus can tag these contributions; i.e., measurements of charm production in different reactions allows us to extract the gluon and $q\bar{q}$ distributions.

Such studies provide us with conceptual insights into the inner workings of QCD; it should lead to a better understanding of the physical interpretation underlying some fit parameters like 'intrinsic' k_T or the notion of 'colour drag'. Secondly a good quantitative knowledge of gluon and $q\bar{q}$ distributions represents 'engineering' input into many other physics studies in hadronic collisions. Finally a better understanding of charm production is needed before it can safely be used as a probe signalling the onset of the quark-gluon phase transition.

(ii) Spectroscopy

There is a rich spectroscopy of the excitations of charm hadrons as reviewed by Kutschke [49]. More surprising at first sight are the contributions that the weak decay studies of charm hadrons are making to the spectroscopy of hadrons carrying light flavour only. Very detailed analyses of the Dalitz plots for $D^+, D_s^+ \to \pi^+\pi^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ have been presented [50]. The emergence of the σ resonance in the $\pi\pi$ channel has been clearly established. Of course, this resonance has been observed before in low energy reactions with much larger statistics. The relevance here does not lie in the statistical significance. The most remarkable point is that the σ emerges in a completely different environment with consistent values for mass and width. I have already mentioned a more surprising role played by the σ: it has been suggested as a relevant factor driving the $\Delta I = 1/2$ rule and ϵ'/ϵ.

The fact that the D_s lifetime exceeds that of D^0 by very close to 20 %, see below, tells us that the *total* D_s widths receives a 10 - 20 % *destructive* contribution from WA. This leads to the obvious question: Can one see the footprint of the latter

	$1/m_c$ expect. [52]	theory comments	data
$\frac{\tau(D^+)}{\tau(D^0)}$	~ 2	PI dominant	2.54 ± 0.03 [55]
$\frac{\tau(D_s^+)}{\tau(D^0)}$	1.0 - 1.07 0.9 - 1.3 1.08 ± 0.04	*without* WA [53] *with* WA [53] QCD sum rules [54]	1.125 ± 0.042 PDG '98 1.18 ± 0.02 [55] E791, CLEO, FOCUS
$\frac{\tau(\Lambda_c^+)}{\tau(D^0)}$	~ 0.5	quark model matrix elements	0.50 ± 0.03 PDG'00
$\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c^+)}$	~ 1.3	ditto	$1.60^{+0.30}_{-0.21}$ PDG'00 2.14 FOCUS, very prelim.
$\frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)}$	~ 2.8	ditto	$3.37^{+0.98}_{-0.65}$ PDG'00 3.56 FOCUS, very prelim.
$\frac{\tau(\Xi_c^+)}{\tau(\Omega_c)}$	~ 4	ditto	5.2 ± 1.8 PDG'00

Table 1: Lifetime ratios in the charm sector

in *exclusive* channels? I find it intriguing that the σ resonance, which manifests itself clearly in $D^+ \to \pi^+\pi^-\pi^+$, is absent in $D_s^+ \to \pi^+\pi^-\pi^+$, while both transitions are affected by WA. These data presumably contain a quite relevant, albeit subtle message which we have not decoded yet.

Lessons about other resonances are being learnt as well in Dalitz plots like $D \to K\bar{K}\pi$ etc.: does the $K\bar{K}$ pair form a resonance, a molecule or simply exhibit a threshold enhancement?

A more speculative idea is to look for glueball candidates G in the hadronic final state of semileptonic D_s decays or in nonleptonic D_s (or Cabibbo suppressed D^+) decays once a fast pion has been removed:

$$D_s[D^+] \to l^+\nu G \quad (22)$$

$$D_s[D^+] \to \pi^+_{fast} G \quad (23)$$

(iii) Lifetimes

On general grounds one expects the following hierarchy in lifetimes [52, 51]:

$$\tau(D^+) > \tau(D^0) \sim \tau(D_s^+) \geq \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c) \quad (24)$$

The $1/m_Q$ expansion can be applied to obtain some more specific predictions which are listed in Table 1 and compared to the data. A few comments are in order here:

- There is agreement between expectations and the data even beyond the qualitative level. This is quite remarkable and not something that one could count on for two reasons. (i) The longest and shortest lifetimes differ by a factor of about twenty. (ii) At the same time one should keep in mind that the charm quark mass exceeds ordinary hadronic scales by a moderate amount only; a $1/m_c$ expansion will therefore be sensitive to higher order terms that cannot be calculated.

- In quoting a predicted lifetime ratio of about two I am well aware that the measured value is different from two. Yet that numerical difference is within the theoretical noise level: one could use $f_D = 220$ MeV rather than 200 MeV and WA, which has been ignored here, could account for 10 - 20 % of the D^0 width.

- PI is the main engine driving the $D^+ - D^0$ lifetime difference as already anticipated in the 'old' analysis of Guberina et al. [45]; the main impact of the HQE for this point was to show that WA cannot constitute the leading effect and that $BR_{SL}(D^0) \simeq 7\%$, $BR_{SL}(D^+) \simeq 17\%$ is consistent with PI being the leading effect [52].

- Since $\tau(D_s)/\tau(D^0) \simeq 1.07$ can be generated *without* WA [53], the 'old' data on $\tau(D_s)/\tau(D^0)$ had provided an independant test for WA *not* being the leading source for $\tau(D^0) \neq \tau(D^+)$; it actually allowed for it being quite irrelevant. The 'new' data reconfirm the first conclusion; at the same time they point to WA as a still significant process. This provides new impetus to uncover the impact of WA on *exclusive* channels like semileptonic modes, 3-pion final states etc., as mentioned above. The more ambitious analysis of Ref.[54] has yielded a value that falls short of the recent measurements.

- The description of the *baryonic* lifetimes is helped by forgiving experimental errors; more accurate measurements of $\tau(\Xi_c^{+,0}, \Omega_c)$ might well exhibit deficiencies in the theoretical description. We heard about two new numbers from FOCUS, which are however still very preliminary without a systematic error given.

- *Non*universal semileptonic widths – $\Gamma_{SL}(D) \neq \Gamma_{SL}(\Lambda_c) \neq \Gamma_{SL}(\Xi_c) \neq \Gamma_{SL}(\Omega_c)$ – are predicted with the main effect being *constructive* PI in Ξ_c and Ω_c decays; the lifetime ratios among the baryons will thus not get reflected in their semileptonic branching ratios; one estimates [56]

$$BR_{SL}(\Xi_c^0) \sim BR_{SL}(\Lambda_c) \quad \leftrightarrow \quad \tau(\Xi_c^0) \sim 0.5 \cdot \tau(\Lambda_c) \tag{25}$$

$$BR_{SL}(\Xi_c^+) \sim 2.5 \cdot BR_{SL}(\Lambda_c) \quad \leftrightarrow \quad \tau(\Xi_c^+) \sim 1.3 \cdot \tau(\Lambda_c) \tag{26}$$

$$BR_{SL}(\Omega_c) \quad < \quad 15\ \% \tag{27}$$

  Unfortunately nothing is known about them experimentally.

(iv) Nonleptonic two-body modes

Very early on it had been conjectured that even the nonleptonic two-body decays of charm hadrons could be described. Including perturbative QCD renormalization of the $\Delta C = 1$ operator leads to the emergence of two multiplicatively renormalized operator $O_\pm$ with short-distance coefficients $c_\pm$. Using this effective weak Lagrangian and some simple prescription for evaluating hadronic matrix elements it was predicted that BR($D^0 \to K^0\pi^0$) $\ll$ BR($D^0 \to K^-\pi^+$) and

$\mathrm{BR}(D^0 \to K^+K^-) \sim \mathrm{BR}(D^0 \to \pi^+\pi^-)$ should hold. Early data showed already that these predictions were quite wrong [4]: the $SU(3)$ breaking in $D^0 \to K^+K^-$ versus $D^0 \to \pi^+\pi^-$ was found to be very large and the expected suppression of $D^0 \to K^0\pi^0$ did not materialize. People then 'rediscovered' that charm decays proceed in an environment populated by many resonances which will affect exclusive modes significantly.

Stech and collaborators made the bold ansatz to describe the nonleptonic two-body charm decays in terms of two effective quantities $a_{1,2}$ which contained both the short-distance coefficients $c_\pm$ and a parameter ξ reflecting the evaluation of the relevant hadronic matrix elements: $a_1 = (c_+ + c_-)/2 + \xi(c_+ - c_-)/2$, $a_2 = (c_+ - c_-)/2 + \xi(c_+ + c_-)/2$. In the valence quark approximation and treating colour degrees of freedom statistically one finds $\xi = 1/N_C = 1/3$.

They also classified the channels into three categories:

$$\text{class I} \;:\; D^0 \to M^+M'^- \tag{28}$$
$$\text{class II} \;:\; D^0 \to M^0M'^0 \tag{29}$$
$$\text{class III} \;:\; D^+ \to M^+M'^0 \tag{30}$$

with class I[II] transitions being described by a_1 $[a_2]$ only; class III channels depend on the interference between a_1 and a_2 terms.

It is quite amazing that a very decent fit could be obtained. For while the ansatz allows for final state interactions, it does so only in a 'universal' sense by lumping them together into the two fit parameters $a_{1,2}$. Even more intriguingly the values found for $a_{1,2}$ were quite consistent with what one obtains when only terms leading in $1/N_C$ (with N_C denoting the number of colours) are retained in the prescription for the matrix elements [57]. Yet ultimately, efforts to gain some deeper understanding through $1/N_C$ expansions did not succeed.

There are several good reasons why the QCD treatment sketched above for nonleptonic beauty decays cannot be applied here; for example, contributions of order $1/m_Q$ that cannot be treated in that scheme are presumably very large here. Nevertheless one should have a look at it.

In any case, these so-called BSW-type studies were and still are very relevant exercises:

- They provide us with some new insights into hadronisation at the interface of perturbative and nonperturbative dynamics. Since these two-body modes make up the bulk of all nonleptonic charm decays, they can teach us novel lessons on quark-hadron duality.

- Such lessons are also quite unique. For nonleptonic two-body modes in B decays being much less frequent and prominent can teach us little about duality

[4] This was the first sign that the decays of charm hadrons were not that simple. Subsequently the first evidence appeared that contrary to expectation the D^+ and D^0 lifetimes differed by a very sizeable factor; that factor appeared to exceed five initially before it settled down to below three.

by themselves. Also class II transitions, often referred to as colour suppressed, are hard to study there because of their tiny branching ratios.

- These studies constitute an essential piece in theoretical engineering in understanding $D^0 - \bar{D}^0$ oscillations and CP violation once they have been observed. I will return to this point later on.

(v) $D \to l\nu$

D_s decays into a purely leptonic final state have been found by several experiments yielding an extraction of the decay constant, as stated above in Eq.(2). At this point I want to stress the particular role played by charm: (i) The branching ratio is much larger for charm than for beauty mesons and thus more accessible experimentally. (ii) At the same time the decay constant is also more accessible to lattice QCD for the charm than the beauty mass scale. To have control over the theoretical uncertainties, one has to go to a fully unquenched treatment, i.e. where all light flavours are treated *dynamically*. Charm studies have now yielded the first partially unquenched results for $f(D)$, namely with two light dynamical flavours. (iii) The two items listed above concern the decay constants as a measure of our theoretical control over QCD. On top of that the decay constants for B and B_s mesons represent also an essential engineering input for interpreting the strength of $B^0 - \bar{B}^0$ oscillations. Of course, one wants to measure $f(B)$ directly. Yet that will be quite a challenge experimentally on top of the fact that $B \to \mu\nu$ depends on $|V(ub)|$ as well. On the other hand if the measured values of $f(D)$ and $f(D_s)$ agree with complete lattice results, this would give us great confidence in the extrapolation of lattice results to the beauty scale.

(vi) $D \to l\nu P/V$

One studies $D \to l\nu K/\pi$ and $D \to l\nu K^*/\rho$ transitions as a check for the theoretical control we have achieved over hadronization effects. Again the motivation is two-fold, namely to check our mastery over QCD and to apply this knowledge to semileptonic B decays where one wants to extract $|V(cb)|$ and $|V(ub)|$. The charm system has the advantage that it is more accessible to *un*quenched lattice studies.

4.2.2 Weak dynamics

(i) Tree level transitions

The full Cabibbo hierachy has been observed now, namely Cabibbo allowed and suppressed channels in semileptonic transitions and Cabibbo allowed, suppressed and doubly suppressed ones in nonleptonic decays [58].

Imposing three-family unitarity one has, see Eq.(8):

$$|V(cs)| = 0.9742 \pm 0.0008\ ,\ |V(cd)| = 0.222 \pm 0.003 \tag{31}$$

Yet without that constraint the values are considerably less precise, see Eq.(9):

$$|V(cs)| = 0.880 \pm 0.096\ ,\ |V(cd)| = 0.226 \pm 0.007 \tag{32}$$

As far as $|V(cs)|$ is concerned the main information from semileptonic D decays is augmented by findings from charm production in deep inelastic neutrino scattering; for $|V(cd)|$ it is the other way around. A recent OPAL analysis [24] of $W \to$ charm jets obtains

$$|V(cs)| = 0.969 \pm 0.058 \tag{33}$$

With charm production and decay rates depending on the charm quark mass, the latter can be extracted from a measurement of those. However this represents a much more involved task than a simple parton model description would suggest. For in a quantum field theory the value of a mass depends not only on the scale at which it is evaluated, but also on how it is defined (and renormalized): does one use a pole or a $\overline{MS}$ or a 'kinetic' mass? Since quarks are confined, there is no natural definition like for electrons. While the pole mass for charm quarks has many convenient features, it suffers from an irreducible theoretical uncertainty of order Λ_{QCD}. The $\overline{MS}$ mass is quite appropriate for production processes well above threshold where typical momenta are large compared to m_c, yet ill-suited for charm decays where momenta are below m_c. In that domain a mass like the 'kinetic' one is much better-suited since it has a softer infrared behaviour [3]. $\overline{MS}$ and kinetic mass are related, but do not coincide even at the same scale.

(ii) Loop transitions

It is often stated that rare charm decays are extremely rare, D^0 oscillations are slow and CP asymmetries tiny within the SM and that therefore their analysis provides us with zero-background searches for New Physics.

With the enhanced experimental sensitivity that has been or will be achieved the real question is: "How slow is slow and how tiny is tiny?"

Flavour changing neutral current transitions $D \to l^+l^-$, $D \to \gamma X$ and $D \to l^+l^-X$ can be generated by effective local operators due to loop effects in analogy to rare B decays. However the resulting branching ratios are absolutely minuscule, even after some huge enhancement due to radiative QCD corrections. Furthermore – and even worse – long distance dynamics induces effects that are larger by orders of magnitude [59].

Oscillations are described by the normalized mass and width differences: $x_D \equiv \frac{\Delta M_D}{\Gamma_D}$, $y_D \equiv \frac{\Delta\Gamma}{2\Gamma_D}$. A very *conservative* SM estimate yields

$$x_D\,,\; y_D \leq \mathcal{O}(0.01) \tag{34}$$

reflecting mainly the fact that the amplitudes for channels communicating between D^0 and $\bar{D}^0$ are proportional to $\mathrm{tg}\theta_C^2 \simeq 0.05$.

The flavour tag in the final state is provided by the charge of the lepton or the kaon in $D^0 \to l^+\nu K^-$ or $D^0 \to K^-\pi's$, respectively. Within the SM with its $\Delta Q = -\Delta C$ rule semileptonic decays provide a clean handle:

$$\frac{\Gamma(D^0 \to l^-X)}{\Gamma(D^0 \to l^+X)} \equiv r_D \simeq \frac{x_D^2 + y_D^2}{2} \tag{35}$$

Decay mode	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$	$D^\pm \to K^+K^-\pi^\pm$
E 791	$-1.0 \pm 4.9 \pm 1.2\%$	$-4.9 \pm 7.8 \pm 3.0\%$	$-1.4 \pm 2.9\%$
CLEO	$0.04 \pm 2.18 \pm 0.84\%$	$1.94 \pm 3.22 \pm 0.84\%$	
FOCUS	$-0.1 \pm 2.2 \pm 1.5\%$	$4.8 \pm 3.9 \pm 2.5\%$	$0.6 \pm 1.1 \pm 0.5\%$

Table 2: Data on direct CP asymmetries in D decays

which can be searched for in time integrated as well as time resolved rates:

$$\frac{d\Gamma(D^0 \to l^- X)}{dt} \propto e^{-\Gamma t} \cdot r_D \cdot (\Gamma t)^2 \tag{36}$$

When using kaons in nonleptonic decays one has to contend with the background from doubly Cabibbo suppressed channels (DCSD) leading to a more complex time evolution

$$\frac{d\Gamma(D^0 \to K^+\pi's)}{dt} \propto e^{-\Gamma t}\left[r_D(\Gamma t)^2 + |\hat{T}_{DCSD}|^2 + |\hat{T}_{DCSD}|y'\Gamma t\right] \tag{37}$$

where

$$\hat{T}_{DCSD} = \frac{T(D^0 \to K^+\pi^-)}{T(D^0 \to K^-\pi^+)} \tag{38}$$

The experimental landscape is described by the following numbers:

$$x_D \leq 0.03 \tag{39}$$

$$y_D = \begin{cases} (0.8 \pm 2.9 \pm 1.0)\% \ \text{E791} \\ (3.42 \pm 1.39 \pm 0.74)\% \ \text{FOCUS} \\ (1.0^{+3.8+1.1}_{-3.5-2.1})\% \ \text{BELLE} \end{cases} \tag{40}$$

$$y'_D = (-2.5^{+1.4}_{-1.6} \pm 0.3)\% \ \text{CLEO} \tag{41}$$

E 791 and FOCUS compare the lifetimes for two different channels, whereas CLEO fits a general lifetime evolution to $D^0(t) \to K^+\pi^-$; its $y'_D = -x_D\sin\delta + y_D\cos\delta$ depends on the strong rescattering phase δ between $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ and therefore could differ substantially from y_D if that phase were sufficiently large [66]. All measurements are still consistent with zero.

The SM with the KM ansatz allows *direct* CP asymmetries in time integrated partial widths to emerge for singly Cabibbo suppressed modes. A benchmark guestimate can be inferred from considering just CKM parameters [60]:

$$\text{asymmetry} \sim \mathcal{O}(\lambda^4) \sim \mathcal{O}(10^{-3}) \tag{42}$$

The analysis of Ref.[61] based on theoretical engineering concerning hadronic matrix elements and strong phase shifts finds somewhat smaller numbers.

Data are summarized in Table 2 [62]. The experimental sensitivity has increased significantly to put us within striking distance of the 1% level. Yet the numbers are still consistent with zero and we are still above the level expected for CKM effects.

4.2.3 First resume

At this point one might subscribe to the following view. There is certainly unfinished business:

- The accuracy with which *absolute* branching ratios are known, in particular for D_s and charm baryon decays, leaves something to be desired;
- likewise for $\Xi_C^{0,+}$ and Ω_c lifetimes as well as the semileptonic branching ratios of charm baryons.
- One wants to have measurements of $D \to l\nu$ and more precise data on $D_s \to l\nu$.
- Post-MARKIII data on lepton *spectra* in *inclusive* semileptonic charm decays would yield important information on the hadronization process.
- One wants to enhance the experimental sensitivity for $D^0 - \bar{D}^0$ oscillations and CP violation.

Such measurements would form important engineering inputs to beauty studies and at the same time produce interesting lessons on nonperturbative QCD dynamics. While the data indeed can be improved and polished, one might be inclined to draw a somewhat cynical summary: "Charm – from a revolutionary to a petit bourgeois!" Such evolutions do indeed often happen in history; I will however argue that it is decidedly wrong here.

4.3 Charm – like Botticelli in the Sistine Chapel

Instead I would characterize the situation by referring to "charm as David Duval versus beauty as Tiger Woods". Colleagues of mine who golf tell me that Duval was widely considered the world's greatest golfer – till Woods appeared on the scene. In presenting my arguments let me proceed from the general to the specific.

- Charm quarks are the only up-type quarks that allow a full range of indirect searches for New Physics:
  - As already mentioned $D^0 - \bar{D}^0$ oscillations can proceed even if slowly; on the other hand there are no $T^0 - \bar{T}^0$ oscillations since top quarks decay before they can hadronize [2].
  - Likewise one can search for CP violation in $D^0 - \bar{D}^0$ oscillations, whereas nothing like that can happen for top states.
  - One can probe for direct CP violation in *exclusive* modes that command decent branching ratios in the charm case. In top decays such branching ratios are truly tiny and the required coherence is basically lost.

- Finally charm decays proceed in an environment populated with many resonances which induce final state interactions (FSI) of great vibrancy. While this feature complicates the interpretations of a signal (or lack thereof) in terms of microscopic quantities, it is optimal for getting an observable signal. In that sense it should be viewed as a glass half full rather than half empty.

- Charm hadrons provide several practical advantages and opportunities:
  - Their production rates are relatively large.
  - They possess long lifetimes.
  - $D^* \to D\pi$ decays provide as good a flavour tag as one can have.

This leads to my basic contention: charm transitions are a *unique* portal for obtaining a *novel* access to the *flavour* problem with the *experimental situation being a priori favourable*!

My discussion in no way aims at downgrading beauty physics – my intention is to point out the qualities of charm studies that are easily overlooked in such a juxtaposition. This is already indicated in the title of this subsection.

4.3.1 $D^0 - \bar{D}^0$ oscillations

Comparing the theoretical bound on $D^0 - \bar{D}^0$ oscillations given in Eq.(34) with the available data tells us that *only now have experiments begun to probe a range of values for x_D and y_D where there is a realistic chance for a non-zero value!* For I find it quite unlikely that New Physics could overcome the second order Cabibbo suppression.

More restrictive bounds than the one stated in Eq.(34) have appeared in the literature. Usually it has been claimed that the contributions from the operator product expansion (OPE) are completely insignificant and that long distance contributions *beyond* the OPE provide the dominant effects yielding x_D^{SM}, $y_D^{SM} \sim \mathcal{O}(10^{-4} - 10^{-3})$. A recent detailed analysis [65] revealed that a proper OPE treatment reproduces also such long distance contributions with

$$x_D^{SM}|_{OPE},\, y_D^{SM}|_{OPE} \sim \mathcal{O}(10^{-3}) \tag{43}$$

and that $\Delta\Gamma$, which is generated from on-shell contributions, is – in contrast to Δm_D – basically insensitive to New Physics while on the other hand more susceptible to violations of (quark-hadron) duality.

The FOCUS data contain a suggestion that the lifetime difference in the $D^0 - \bar{D}^0$ complex might be as large as $\mathcal{O}(1\%)$. *If* y_D indeed were ~ 0.01, two scenarios could arise for the mass difference. If $x_D \leq$ few $\times 10^{-3}$ were found, one would infer that the $1/m_c$ expansion yields a correct semiquantitative result while blaming the large value for y_D on a sizeable and not totally surprising violation of duality. If on

the other hand $x_D \sim 0.01$ would emerge, we would face a theoretical conundrum: an interpretation ascribing this to New Physics would hardly be convincing since $x_D \sim y_D$. A more sober interpretation would be to blame it on duality violation or on the $1/m_c$ expansion being numerically unreliable. Observing D^0 oscillations *per se* then would not constitute an unambiguous signal for New Physics. Yet if indeed $y_D \geq 0.01$ were established, it would represent undoubtedly an important discovery even if the intrepretation were ambiguous.

Since the main motivation is to uncover New Physics, one should not treat the SM $\Delta Q = -\Delta C$ rule as sacrosanct, but entertain the notion that $e^{\Gamma t} d\Gamma(D^0(t) \to l^- X)/dt$ might contain a genuine time independant contribution.

4.3.2 CP violation involving $D^0 - \bar{D}^0$ oscillations

The interpretation is much clearer once one finds a CP asymmetry that involves oscillations; i.e., one compares the time evolution of transitions like $D^0(t) \to K_S \phi$, K^+K^-, $\pi^+\pi^-$ and/or $D^0(t) \to K^+\pi^-$ with their CP conjugate channels. A difference for a final state f would depend on the product

$$\sin(\Delta m_D t) \cdot \mathrm{Im}\frac{q}{p}[T(\bar{D} \to f)/T(D \to \bar{f})] \ . \tag{44}$$

I want to stress two aspects of this expression:

- With both factors being $\sim \mathcal{O}(10^{-3})$ in the SM with the KM ansatz one predicts a practically zero asymmetry $\leq 10^{-5}$.

- New Physics could quite conceivably generate considerably larger values, namely $x_D \sim \mathcal{O}(0.01)$, $\mathrm{Im}\frac{q}{p}[T(\bar{D} \to f)/T(D \to \bar{f})] \sim \mathcal{O}(0.1)$ leading to an asymmetry of $\mathcal{O}(10^{-3})$.

- One should note that the oscillation dependant term is linear in the small quantity x_D
$$\sin \Delta m_D t \simeq x_D t/\tau_D \tag{45}$$
in contrast to r_D which is quadratic:
$$r_D \equiv \frac{D^0 \to l^- X}{D^0 \to l^+ X} \simeq \frac{x_D^2 + y_D^2}{2} \tag{46}$$
It would be very hard to see $r_D = 10^{-4}$ in CP insensitive rate. It could then well happen that $D^0 - \bar{D}^0$ oscillations are first discovered in such CP asymmetries!

4.3.3 Direct CP violation

(i) Partial widths

There are three requirements for an asymmetry to become observable between CP conjugate partial widths, namely (i) two coherent amplitudes with (ii) a relative *weak* phase and (iii) a nontrivial strong phase shift.

In Cabibbo favoured as well as in doubly Cabibbo suppressed channels those requirements can be met with New Physics only. There is one exception to this general statement: the transition $D^{\pm} \to K_S \pi^{\pm}$ reflects the interference between $D^+ \to \bar{K}^0 \pi^+$ and $D^+ \to K^0 \pi^+$ which are Cabibbo favoured and doubly Cabibbo suppressed, respectively. Furthermore in all likelihood those two amplitudes will exhibit different phase shifts since they differ in their isospin content [63].

There is one effect that has to be there without any theory uncertainty and without New Physics, namely an asymmetry driven by the CP impurity in the K_S state:

$$\frac{\Gamma(D^+ \to K_S \pi^+) - \Gamma(D^- \to K_S \pi^-)}{\Gamma(D^+ \to K_S \pi^+) + \Gamma(D^- \to K_S \pi^-)} = -2\mathrm{Re}\epsilon_K \simeq -3.3 \cdot 10^{-3} \tag{47}$$

In that case the same asymmetry both in magnitude as well as sign arises for the experimentally much more challenging final state with a K_L. If on the other hand New Physics is present in $\Delta C = 1$ dynamics, most likely in the doubly Cabibbo transition, then both the sign and the size of an asymmetry can be different from the number in Eq.(47), and by itself it would make a contribution of the opposite sign to the asymmetry in $D^+ \to K_L \pi^+$ vs. $D^- \to K_L \pi^-$.

Searching for *direct* CP violation in Cabibbo suppressed D decays as a sign for New Physics would also represent a very complex challenge: within the KM description one expects to find some asymmetries of order 0.1 % [61]; yet it would be hard to conclusively rule out some more or less accidental enhancement due to a resonance etc. raising an asymmetry to the 1% level. Observing a CP asymmetry in charm decays would certainly be a first rate discovery even irrespective of its theoretical interpretation, as it is with respect to ϵ'/ϵ. Yet to make a case that a signal in a singly Cabibbo suppressed mode reveals New Physics is quite iffy. In all likelihood one has to analyze at least several channels with comparable sensitivity to acquire a measure of confidence in one's interpretation.

(ii) Final state distributions

For channels with two pseudoscalar mesons or a pseudoscalar and a vector meson a CP asymmetry can manifest itself only in a difference between the two partial widths, as just discussed. If, however, the final state is more complex – being made up by three pseudoscalar or two vector mesons etc. – then it contains more dynamical information than expressed by its partial width and CP violation can emerge also through asymmetries in final state distributions. One general comment still applies: since also such CP asymmetries require the interference of two weak amplitudes, within the SM they can occur in Cabibbo suppressed modes only.

In the simplest such scenario one compares CP conjugate *Dalitz plots*. I have noticed that Dalitz plot studies are very popular with our colleagues in Rio de Janeiro. Having come here I understand why: the topography of Rio with its steeply rising mountain ranges crowned by spectacular peaks and separated by narrow valleys is

a dramatic large scale model of a Dalitz plot.

In the present context I want to stress the following: it is quite possible that different regions of a Dalitz plot exhibit CP asymmetries of varying signs that largely cancel each other when one integrates over the whole phase space. I.e., subdomains of the Dalitz plot could contain considerably larger CP asymmetries than the integrated partial width.

Once a Dalitz plot is fully understood with all its resonance and non-resonance contributions including their strong phases, one has a powerful and sensitive new probe. This is not an easy goal to achieve, though, in particular when looking for effects that presumably are not overly large. It might be more promising as a practical matter to start out with a more euristic approach. Let me remind you of a quote by someone who often appears to be one of the founding fathers of the American school of philosophy, namely Yogi Berra [5]; he once declared: "You can always start an observation of something by looking at it!" My point is that we have still to learn the tricks of the trade; this is best done by analysing data to see what can happen. While some relevant experience exists from analyses of $K \to 3\pi$, the situation is considerably more involved in charm decays where the much larger phase space allows for many resonances to make their presence felt.

I therefore suggest to undertake one's search for an asymmetry in an open-minded fashion. One simple strategy would be to focus on an area with a resonance band and analyze the density in stripes *across* the resonance as to whether there is a difference in CP conjugate plots.

For more complex final states containing four pseudoscalar mesons etc. other probes have to be employed. Consider for example

$$D^0 \to K^+ K^- \pi^+ \pi^- \ , \tag{48}$$

where one can form a T-odd correlation with the momenta:

$$C_T \equiv \langle \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \rangle \tag{49}$$

Under time reversal T one has

$$C_T \to -C_T \tag{50}$$

hence the name 'T-odd'. Yet $C_T \neq 0$ does not necessarily establish T violation. Since time reversal is implemented by an *anti*unitary operator, $C_T \neq 0$ can be induced by final state interactions (FSI). While in contrast to the situation with partial width differences FSI are not required to produce an effect, they can act as an 'imposter' here, i.e. induce a T-odd correlation with T-invariant dynamics. This ambiguity can unequivoally be resolved by measuring

$$\bar{C}_T \equiv \langle \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \rangle \tag{51}$$

[5]Interestingly enough he practised Einstein's dictum that one should not do one's deep thinking in one's paid job.

in $\bar{D}^0 \to K^+K^-\pi^+\pi^-$; finding

$$C_T \neq -\bar{C}_T \tag{52}$$

establishes CP violation without further ado!

Decays of *polarized* charm baryons provide us with a similar class of observables; e.g., in $\Lambda_c \Uparrow \to p\pi^+\pi^-$, one can analyse the T-odd correlation $\langle \vec{\sigma}_{\Lambda_c} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \rangle$ [64].

4.3.4 Benchmark numbers

Without a clearcut theory of New Physics one has to strike a balance between the requirements of feasibility and the demands of making a sufficiently large step beyond what is known when suggesting benchmark numbers for the experimental sensitivity to aim at. In that spirit I suggest the following numbers:

- Probe $D^0 - \bar{D}^0$ oscillations down to x_D, $y_D \sim \mathcal{O}(10^{-3})$ corresponding to $r_D \sim \mathcal{O}(10^{-6} - 10^{-5})$.

- Search for *time dependant* CP asymmetries in $D^0(t) \to K^+K^-$, $\pi^+\pi^-$, $K_S\phi$ down to the 10^{-4} level and in the doubly Cabibbo suppressed mode $D^0(t) \to K^+\pi^-$ to the 10^{-3} level.

- Look for asymmetries in the partial widths for $D^\pm \to K_{S[L]}\pi^\pm$ down to 10^{-3} and likewise in a *host* of singly Cabibbo suppressede modes.

- Analyze Dalitz plots and T-odd correlations etc. with a sensitivity down to $\mathcal{O}(10^{-3})$.

4.4 The future: expectations, promises and dreams

It is guaranteed that the data base on charm physics will be expanded tremendously in the several next years: FOCUS and SELEX will presumably present their full analysis not later than at the next meeting in this series two years from now; the e^+e^- beauty factories at KEK, SLAC and Cornell will produce a large amount of high quality data over the next several years; COMPASS will make contributions as well.

There is considerable promise that BTEV and LHC-b can harness the large statistics of charm decays occurring in hadronic collisions for further studies that might achieve a new statistical quality.

Finally there are the 'gleam in the eye' plans for novel initiatives: a τ-charm factory at Cornell, deep inelastic neutrino scattering at ν factories and a glue-charm factory at GSI.

Studies of charm hadrons have had an illustrious past; they were instrumental in the Standard Model gaining universal acceptance. Yet they are not a closed chapter; they have the potential to point the way to New Physics. This educated hope can

be expressed in a phrase borrowed from the political scene: *"Charm physics: You haven't seen anything yet – the best things are still to come!"*

5 The outlook

Advances do not occur in a continuous fashion. Long periods of seemingly little progress are often followed by short periods of rapidly happening new developments that sometimes lead even to a new paradigm. As I have stated in the beginning we have entered such a special period for heavy quark flavour physics, in particular with respect to CP violation. The existence of direct CP violation has been established in K_L decays, we are on the brink of observing for the first time CP asymmetries in a different system, namely in beauty decays, and the hope for finding such effects in charm decays no longer has to be based on "irrational exuberance" [6]. Experimental studies relying on refined theoretical tools might well reveal an incompleteness of the Standard Model in the foreseeable future. I would like to emphasize in this context that no findings in beauty physics – no matter whether they are positive or negative, whether they reveal New Physics or not – can eliminate the need for a dedicated high sensitivity program on charm (and top) transitions. [7]

One of the puzzles of the SM, namely why neutrinos are massless, might be solved now: they are actually not massless since they show signs of oscillations! Neutrinos being very light is naturally understood through the 'see-saw' mechanism. Such findings open the gates to vast new domains of dynamics characterised by the emergence of a leptonic analogue to the CKM matrix, namely a nontrivial MNS matrix for lepton flavours [67]. Effects will be even more subtle than their quark analogues, and searches for them will severely test our patience and dedication. Yet having a family structure with its lepton-quark correspondances it makes eminent sense for the flavour dynamics to stand on two legs, even if one is stronger than the other. I am also extremely pleased that the organizers of this series of meetings react substantially to these developments by changing the name of the series to 'Heavy Quark and Lepton Flavours'. At the same time I would like to urge the organizers to maintain the tradition of giving many time slots to younger speakers (which means substantially younger than yours truly).

Finally I would like to thank Alberto Reis and his team in Brazil for creating such a wonderful atmosphere for the meeting and being such gracious hosts. In addition I want to express my deep appreciation and gratitude for their pioneering

[6]To say that data had not yielded a qualitatively new result for more than thirty years does not reflect a deeper truth. New empirical insights typically are not born like the goddess Athene who jumped fully developed and in full armour out of Zeus', her father's, head. They require substantial incubation periods.

[7] Rio is experiencing a phenomenon of manifest symbolism for our agenda: penguins are showing up at the beaches in record numbers. The reasons underlying that migration are not clear. The penguins arrive in poor shape needing care; apparently they come against their will, and the people do not know what to do with them, see http://www.sueddeutsche.de/news/pinguine.htm.

work at CBPF and their universities in creating a home for fundamental reasearch in general and high energy physics in particular in the southern hemisphere of our world!

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